



Orbiter Entry Aerothermodynamics Practical Engineering and Applied Research

Charles H. Campbell

Orbiter Entry Boundary Layer Transition Flight Experiment

Principal Investigator

Applied Aerosciences and CFD Branch

NASA Johnson Space Center, Houston, TX

May 12th, 2009

Invited Presentation at Stanford University

Mechanical Engineering Department

Fluid Mechanics Seminar

STS-114 Launch on July 26th, 2005





Orbiter Return to Flight Aeroheating



- **Outline**
 - Organization of the Orbiter Entry Aeroheating Working Group
 - Overview of the Principal RTF Aeroheating Tools Utilized for Tile Damage Assessment
 - Description of the Integrated Tile Damage Assessment Team Analyses Process
 - Space Shuttle Flight Support Process
 - JSC Applied Aerosciences and CFD Branch Applied Research Interests

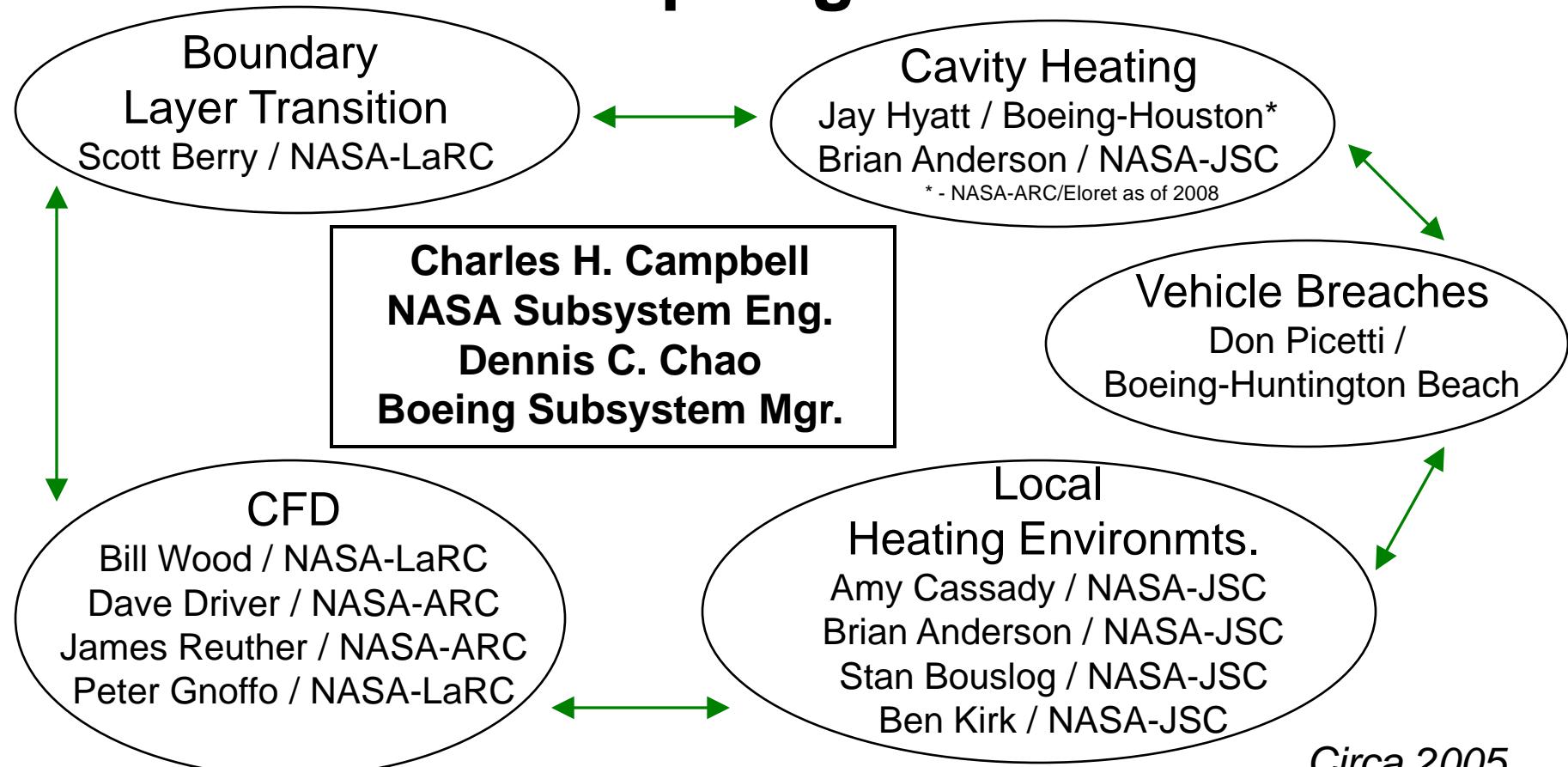


Orbiter Return to Flight Aeroheating



Orbiter Entry Aeroheating Working Group Organization

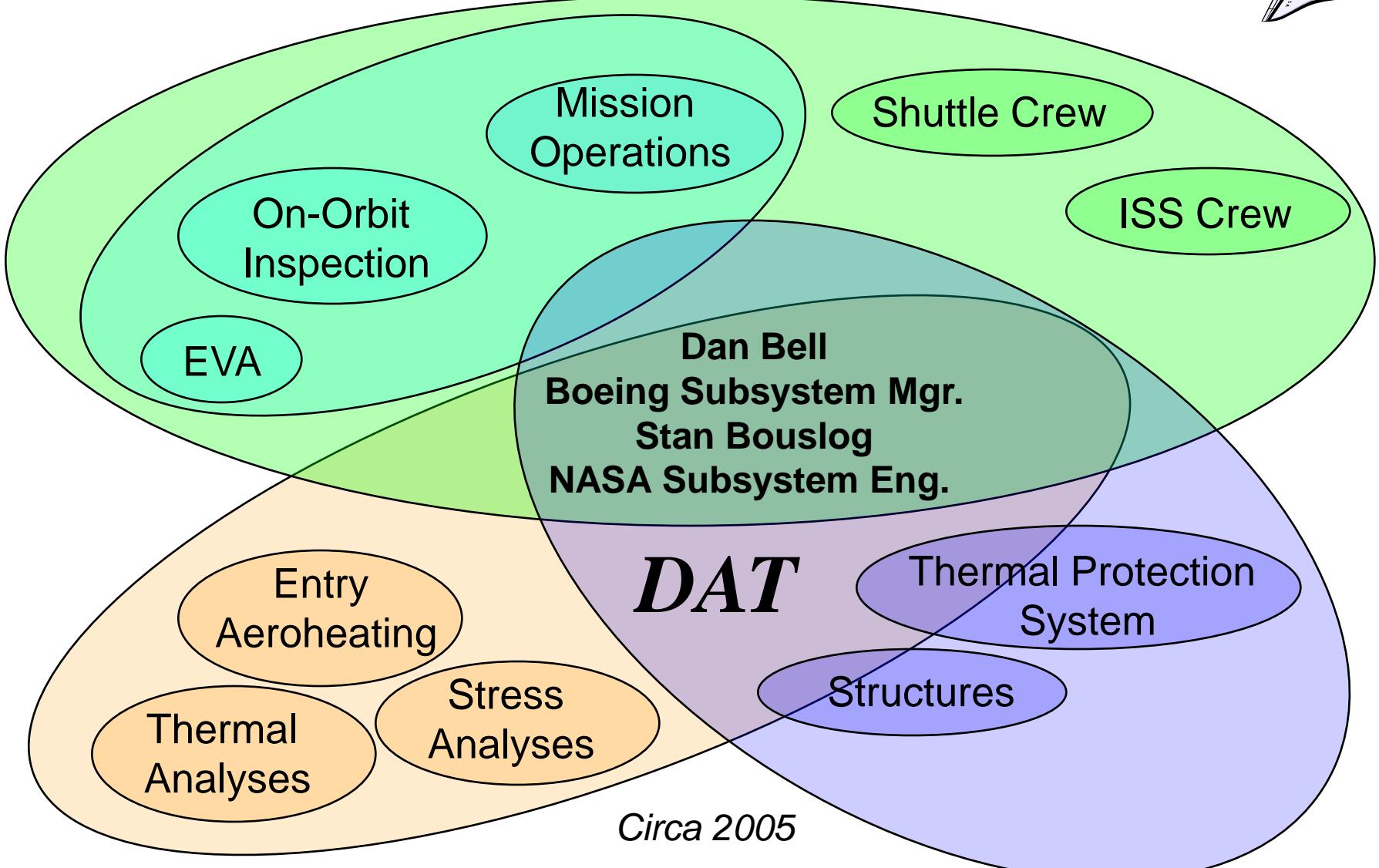
Ref: Campbell et al, AIAA-2006-2917



Circa 2005

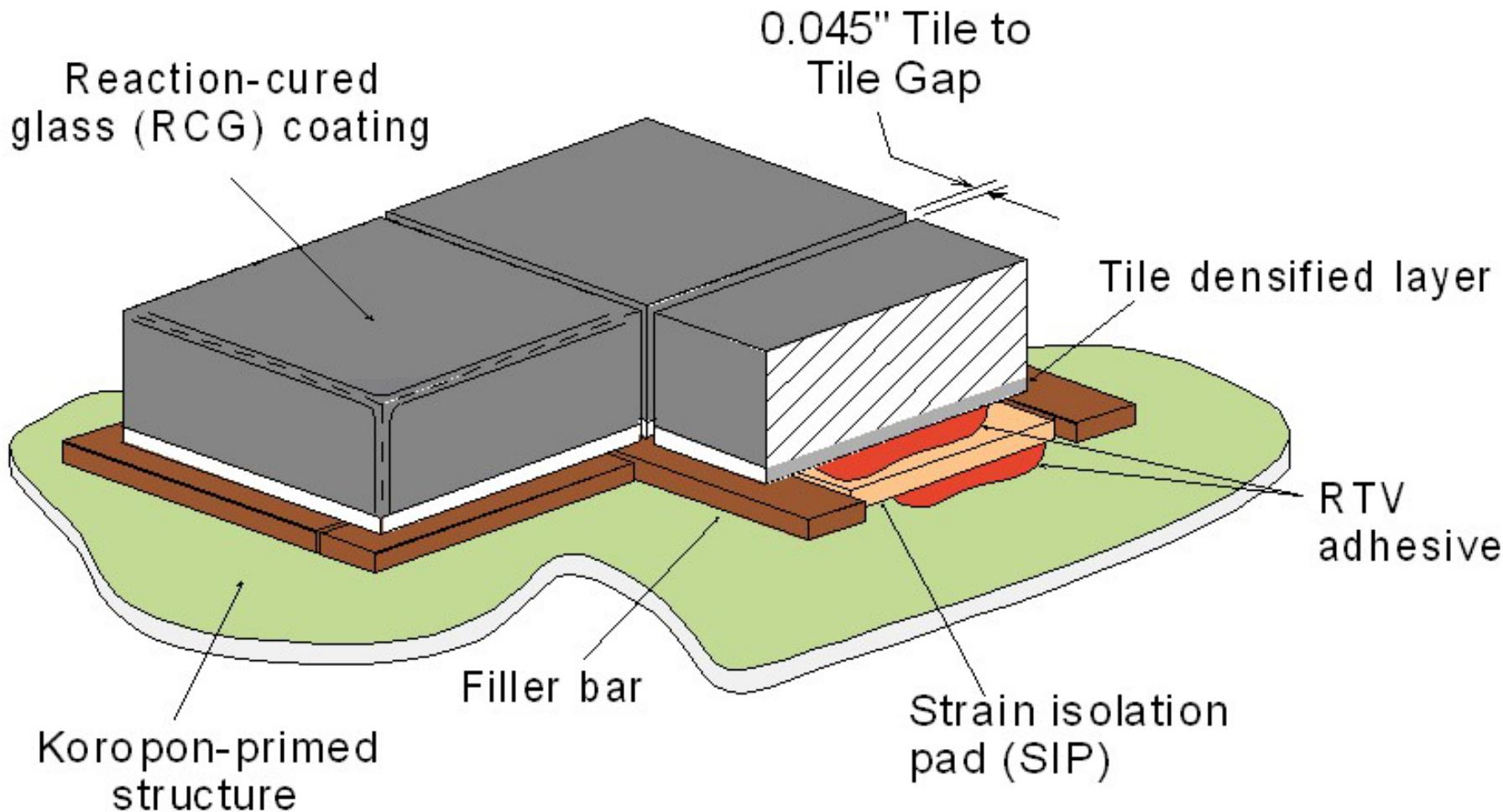


Tile Damage Assessment Team





Tile System Description



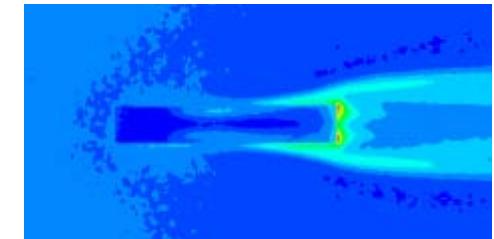


Orbiter Return to Flight Aeroheating



- Principal Aeroheating Tools for DAT
 - XF0002 / Nominal Convective Heating
 - Utilizes simplified heating methods for > 2000 OML locations
 - Phenomenology: Temperature based heat transfer coefficient
 - Developed during Orbiter DDT&E
 - Calibrated to Orbiter flight data
 - Catalytic Heating / Uncoated Tile catalycity
 - Based on preliminary arc-jet data
 - Utilizes a simple bump factor relationship
 - Cavity Heating / Damaged tile cavity heating
 - Updates for laminar effects based on wind tunnel data
 - Phenomenology: Temperature based heat transfer coefficient
 - Historical turbulent correlation based on extant experimental data
 - Methodology Utilizes Engineering correlations
 - Shallow Cavity (new)
 - Everhart Cavity (new)
 - Closed Cavity (new)
 - Turbulent Cavity (historical Boeing method)

NASA LaRC Mach 10
Thermographic Phosphor Cavity Heating



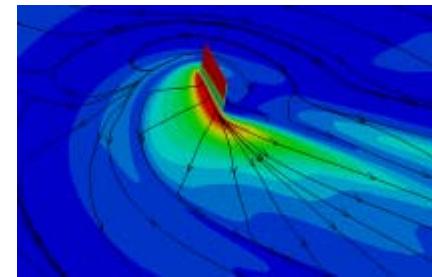
Ref: Everhart et al, AIAA-2006-185



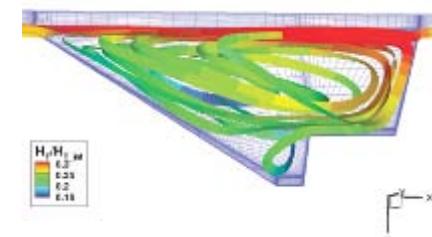
Orbiter Return to Flight Aeroheating



Protrusion CFD Simulation



Flight Cavity CFD Simulation



- **Principal Aeroheating Tools for DAT (cont'd)**

- **Rapid Assessment CFD**

- Utilizes DPLR and LAURA
 - Nonequilibrium chemistry, Navier-Stokes solvers
 - Calibrated to available cavity experimental data
 - Leverages multiple capabilities to satisfy efficiency needs
 - Automated grid generation
 - Repository of Smooth Baseline Orbiter solutions
 - Sub-zone decomposition to solve local damage region
 - NAS Columbia system for rapid turn-around

- **Boundary Layer Transition**

- Methodologies developed for Protuberances and Cavities
 - Principal data sets from NASA-LaRC Mach 6 and 10 air tunnels
 - Complementary data from AEDC MH-11 Orbiter test (ca. 1993) and CUBRC MH-13 Orbiter test
 - Correlations established for wind tunnel data and calibrated to available Orbiter flight data
 - Relies on Boundary Layer Properties tool to provide edge conditions in flight envelope
 - Flight Envelope and Wind Tunnel databases established with DPLR and LAURA Nonequilibrium N.S.

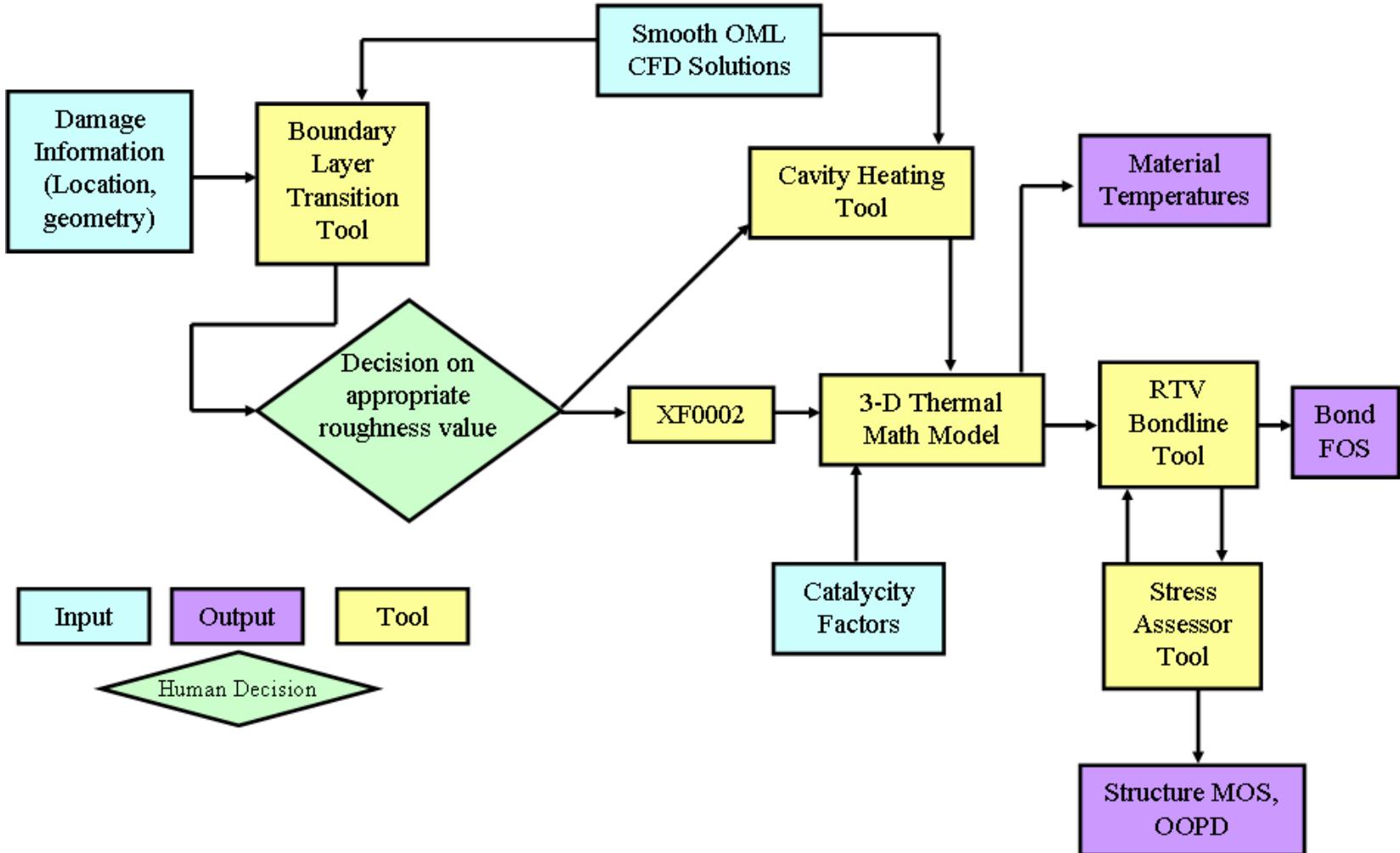
Ref: Palmer et al, AIAA-2007-4254
Pulsonetti et al, AIAA-2005-4679



Tile Damage Assessment Team

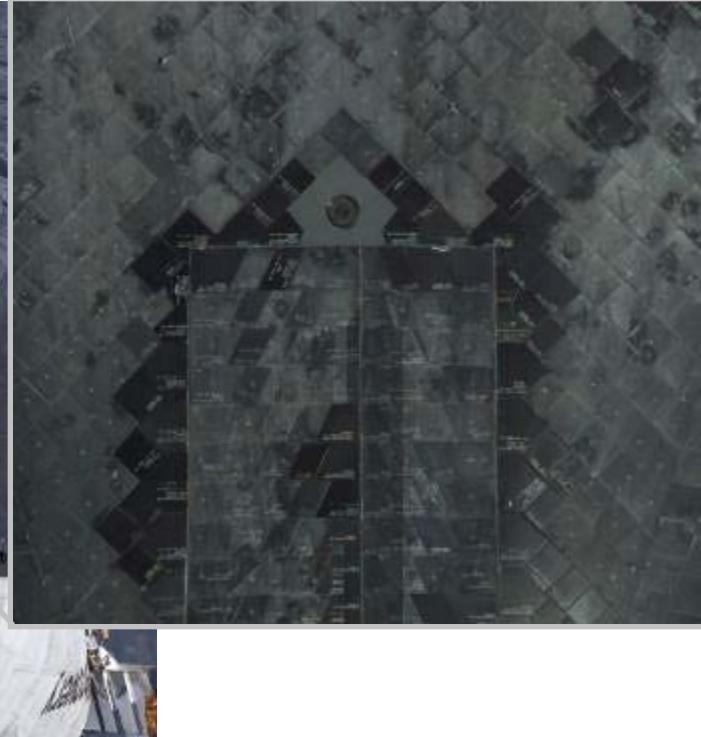


Flight Support Process





STS-114 Damage Assessment



Assessments Required

- 4 windward sites
- 2 protruding gap fillers
- 1 blanket (leeside)



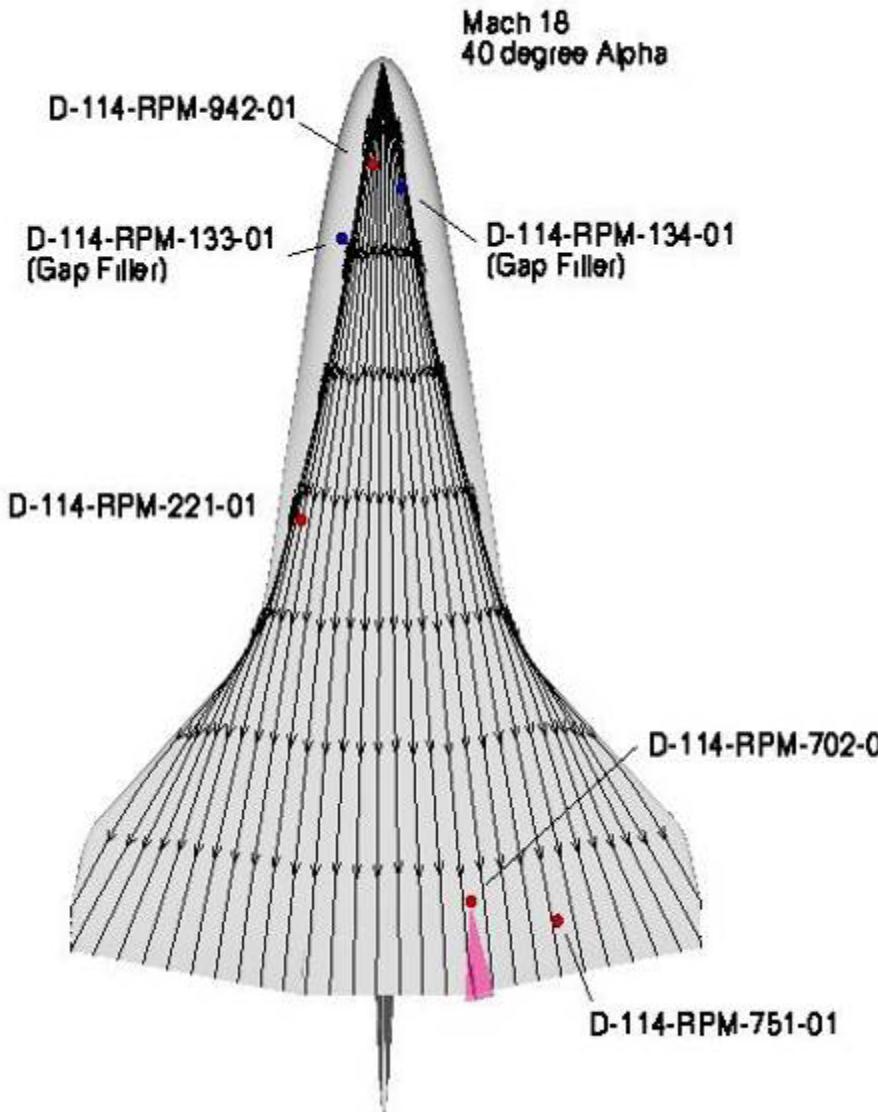
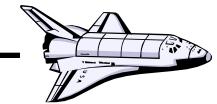
Damage Assessment Since STS-114



STS Mission	Launch	Entry	Total Damage Sites Examined by Damage Assessment Team
STS-114	July 26, 2005	August 9, 2005	49
STS-121	July 4, 2006	July 17, 2006	13
STS-115	September 9, 2006	September 21, 2006	28
STS-116	December 9, 2006	December 22, 2006	10
STS-117	June 8, 2007	June 22, 2007	11
STS-118	August 8, 2007	August 21, 2007	25
STS-120	October 23, 2007	November 7, 2007	14
STS-122	February 7, 2008	February 20, 2008	17
STS-123	March 10, 2008	March 26, 2008	20
STS-124	May 31, 2008	June 14, 2008	14
STS-126	November 14, 2008	November 30, 2008	13
STS-119	March 15, 2009	March 28, 2009	10

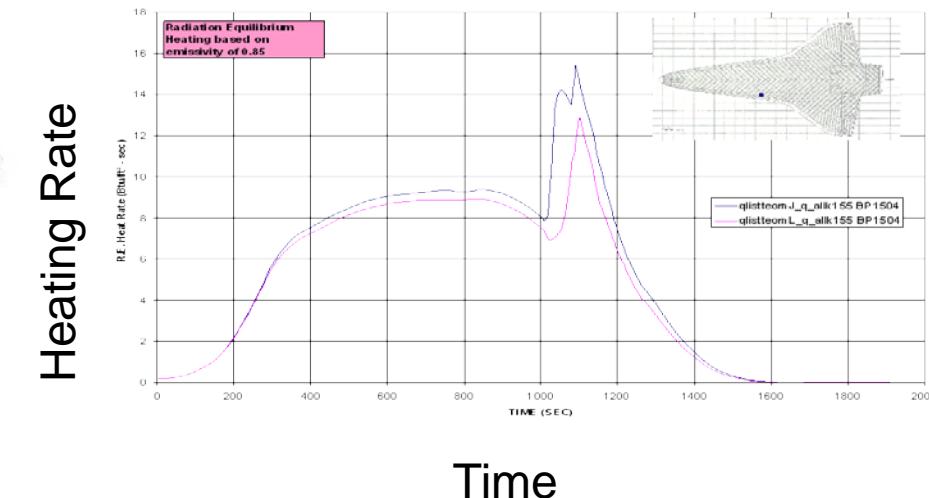


STS-114 Damage Assessment



Aeroheating Team Report Info

- Windward view (to left)
- Turbulent Influence zone
- BLT Predictions for each site
- Reference Heating
- Cavity Heating summary

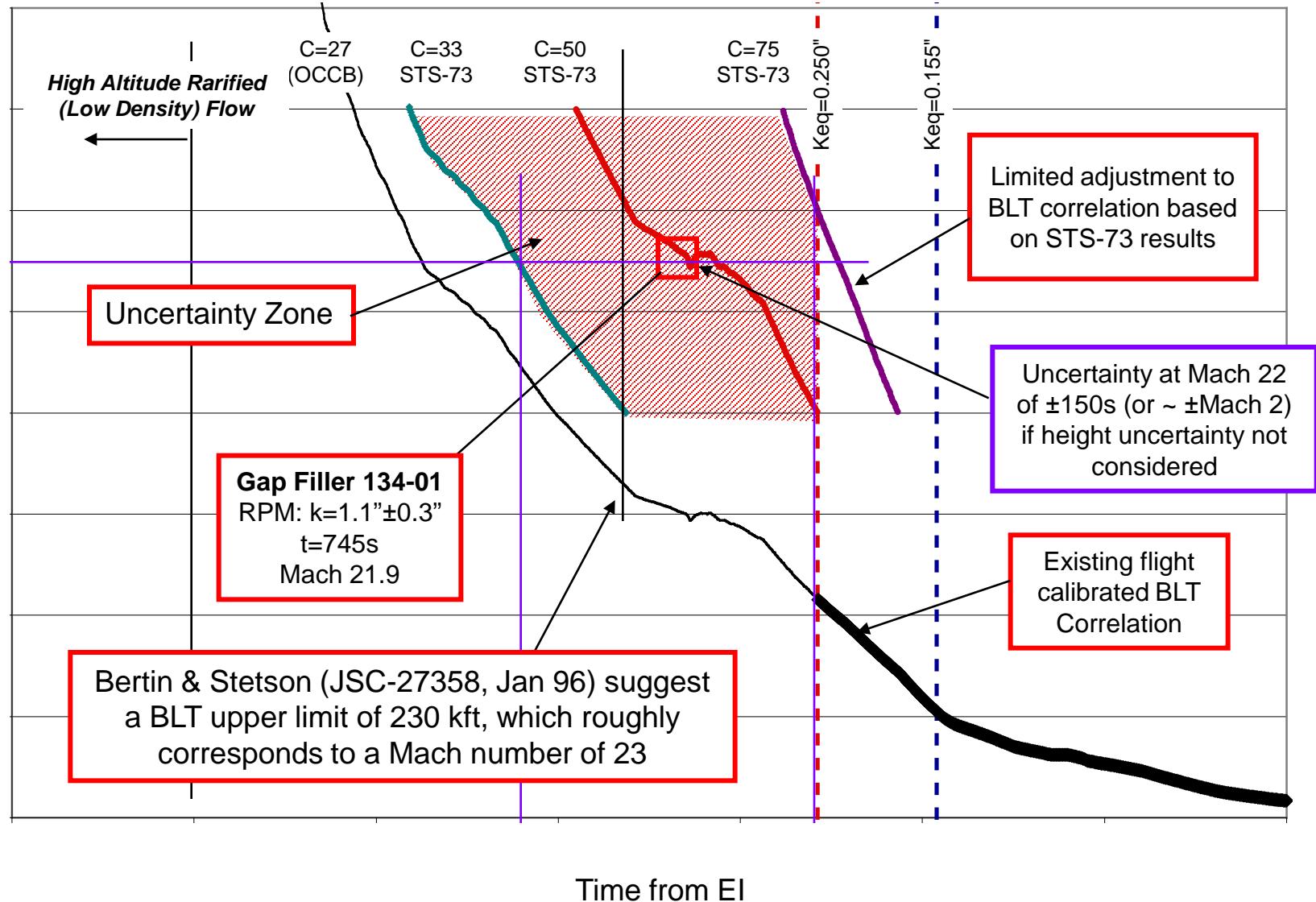




STS-114 Gap Filler Assessment

$$K=C(\delta)/(R\theta/M) \text{deg}$$

Height required for transition onset

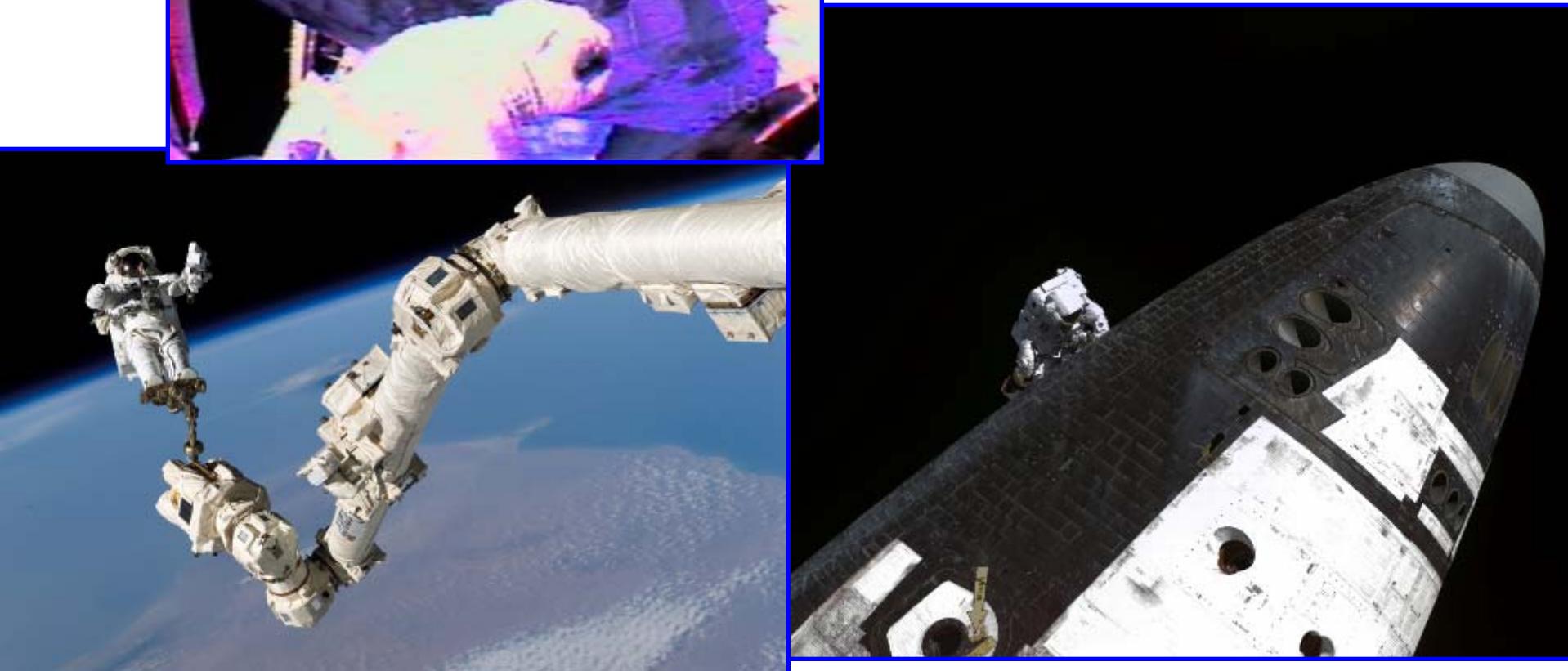




STS-114 Gap Filler Removal



Stephen R. Robinson
and Soichi Noguchi
performed the first ever
on-orbit TPS repair
on August 3, 2005





STS-117 OMS Pod Blanket Repair



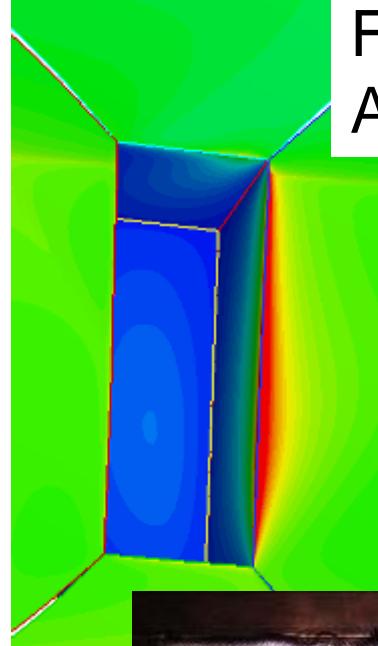
On-Orbit,
prior to repair



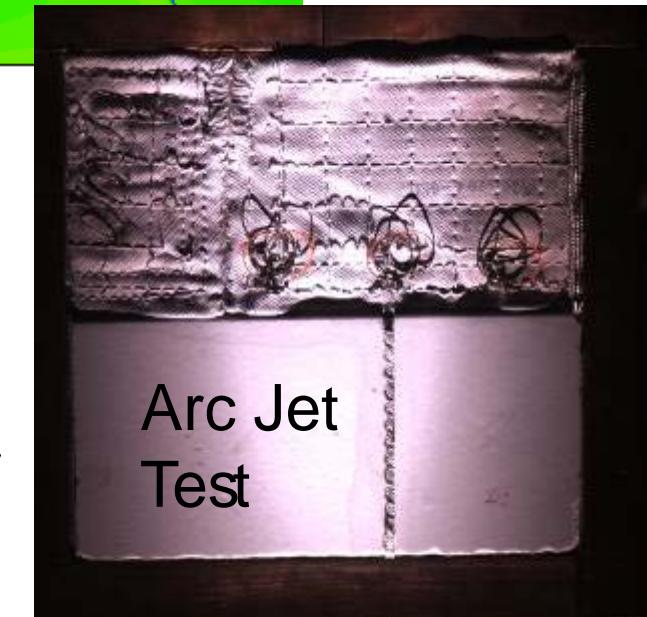
Post
Landing



Danny Olivas
performed the first ever
on-orbit OMS Pod repair
on June 15, 2007



Flight CFD
Assessment



Arc Jet
Test



Stephen Robinson portrait after STS-114 Gap Filler Repair

vsn5 May 7, 2009

presenter - Charles H. Campbell / NASA JSC /
charles.h.campbell@nasa.gov



Danny Olivas self-portrait after STS-117 OMS Pod Blanket Repair

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presenter - Charles H. Campbell / NASA JSC /
charles.h.campbell@nasa.gov



JSC Aerosciences Branch

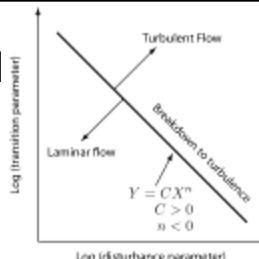
Current Applied Research Interests

- Boundary Layer Transition Prediction
 - Engineering Correlations (NASA)
 - Stability modeling (University of Minnesota/Candler, Johnson)
- Quiet Hypersonic Experimental Capabilities
 - Purdue Mach 6 Quiet Tunnel (Schneider, et al)
- Hypersonic wind tunnel non-intrusive measurement
 - Planar Induced Fluorescence (LaRC / Danehy, et al.)
- Roughness Induced Augmented Heating
 - Crew Exploration Vehicle (CEV) Heat Shield (JSC / Amar, et al.)
- Hypersonic Expansion Tunnels
 - CUBRC LENS-XX (Holden, et al.)
- Other topics related to aerosciences



Discrete Roughness BLT

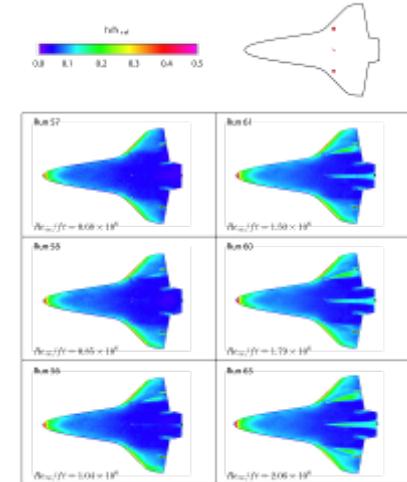
- Develop engineering tool for rapid Orbiter transition prediction. A generalized correlation approach was implemented.



Model in LaRC 20-Inch Mach 6

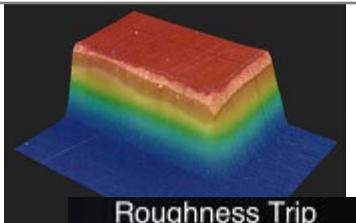


Phosphor Thermography Data

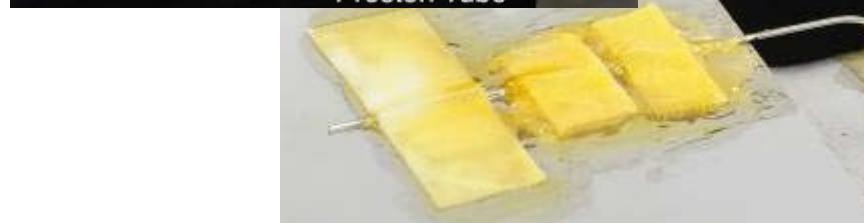


References:

- King R.A., et al., JSC EG-SS-07-07, 2007.
- McGinley, C.B., et al., AIAA 2006-2921.
- Liechty, D.S., et al., NASA/TM 2006-214306.
- Cassady, A.M., et al., NASA/TP 2007-214758.
- King, R.A., et al., NASA/TM 2008-215103.



Rudy King, Mike Kegerise



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charles.h.campbell@nasa.gov

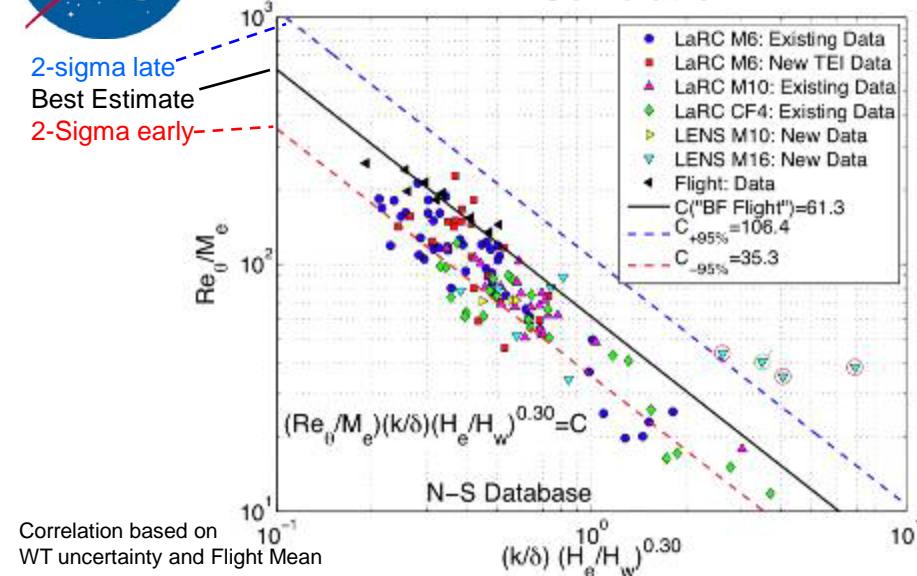
Future work supported by Hypersonics Program in the Fundamental Aeronautics Program / ARMD.

- Investigate effects of discrete roughness on stability & transition of Zero Pressure Gradient BL in a Mach 3.5 quiet tunnel.
- Objective is to understand the underlying physics leading to BLT that may ultimately lead to improved physics-based correlation methodologies.
- Acquire off-surface measurements of BL disturbance field, both mean and fluctuating components.



Orbiter Return To Flight BLT Correlation

RTF BLT V2 Correlation



Proposed Correlation	Correlation Equation	Ground-Based			Ground-Based + Flight		
		R	$\Delta C/C$	σ_C/\bar{C}	R	$\Delta C/C$	σ_C/\bar{C}
1	$Re_\theta/M_e \times k/\delta = C$	-0.87	1.26	19.9%	-0.88	1.25	21.2%
2	$Re_\theta/M_e \times k/\delta^* = C$	-0.90	1.08	7.3%	-0.87	1.32	34.9%
3	$Re_\theta/M_e \times (k/\delta)(T_e/T_w)^{0.16} = C$	-0.89	1.14	14.5%	-0.89	1.20	23.6%
$\Rightarrow 4$	$Re_\theta/M_e \times (k/\delta)(H_e/H_w)^{0.30} = C$	-0.91	1.04	8.9%	-0.91	1.10	19.9%
5	$\rho_k u_k k / \mu_w = C$	-0.79	2.51	30.9%	—	—	—
$\Rightarrow 6$	$Re_k^{0.8} \times [Re_\theta \cdot (\mu_e / \mu_k)]^{0.4} = C^*$	-0.87	1.09	14.8%	-0.84	1.30	35.0%

* Results are for $n = -0.6$ for all data.

Accuracy of various BLT Engineering Correlations with Orbiter RTF Data

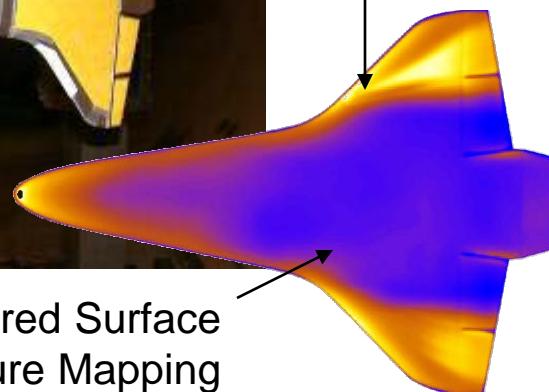
Ref: King, R.A., Kegerise, M.A. and Berry, S.A., "Proposed Protuberance Correlations for the Next Generation BLT Tool (vsn 2)", EG-22-07-07, March 30, 2007

CUBRC MH-13
Wind Tunnel Model



Cassady, et al
NASA/TP-2007-214758

Turbulent Wedge from BLT Trip

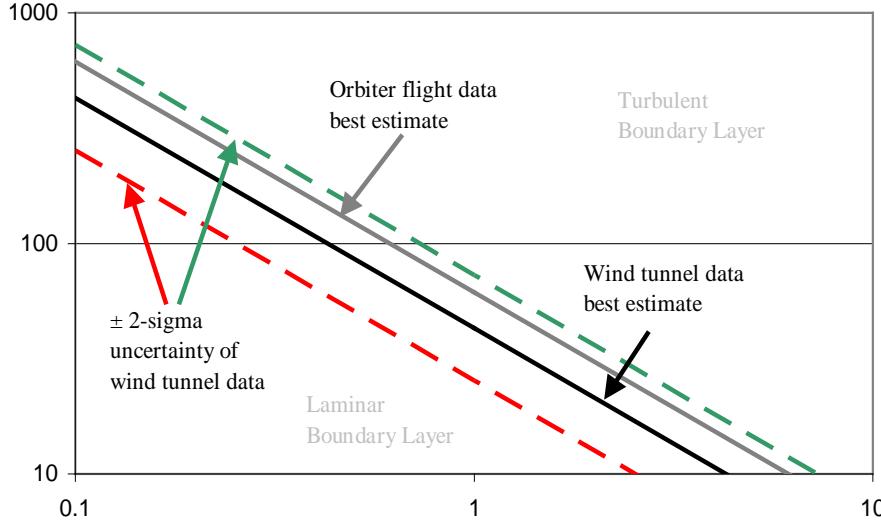


LaRC Infrared Surface Temperature Mapping

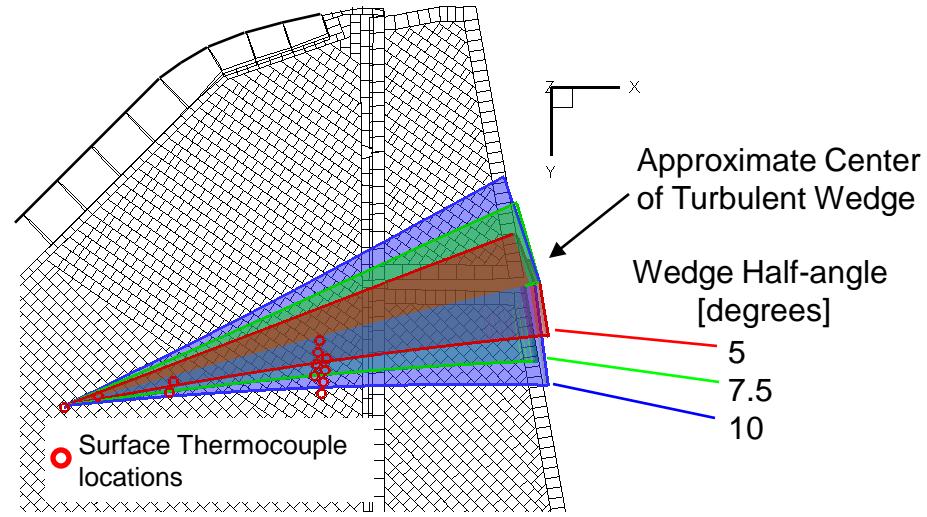


Orbiter BLT Flight Experiment Context

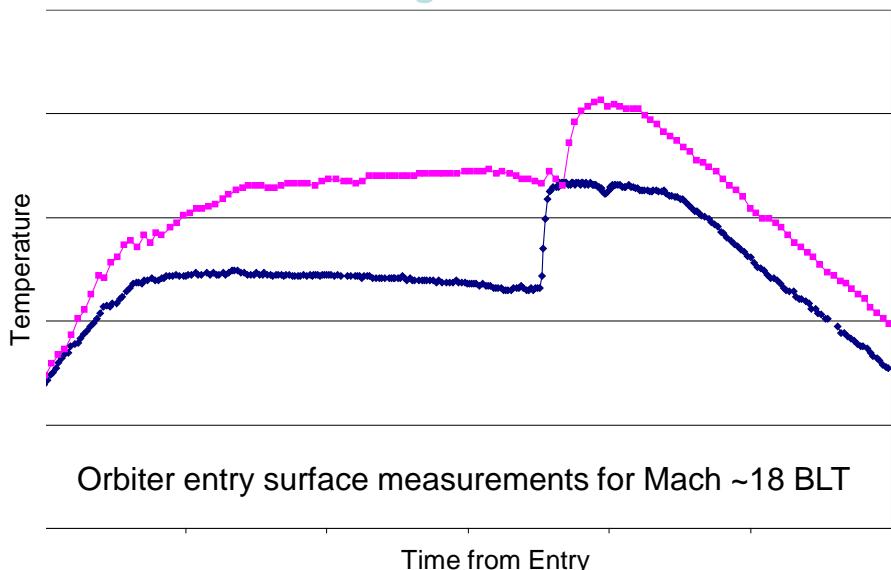
RTF BLT V2 Correlation



Turbulent Wedge



Aeroheating Environments



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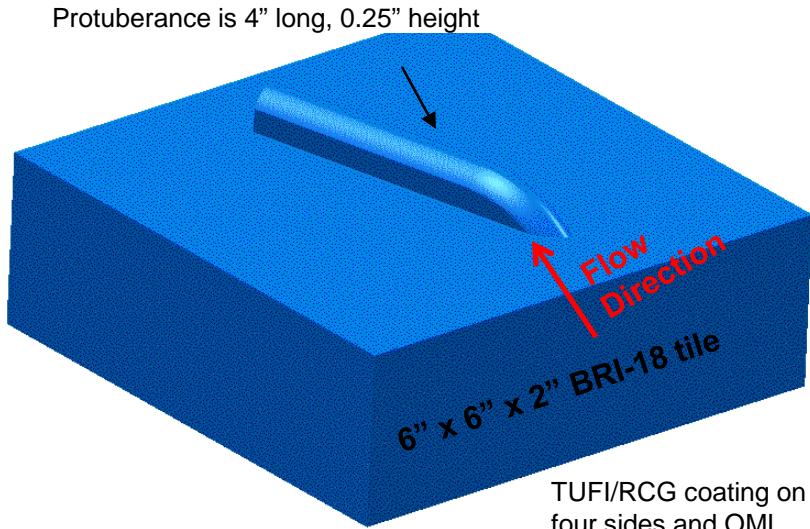
Comments

- Current Orbiter flight data BLT uncertainty is similar to correlation uncertainty (*small data sample, geometry uncertainty, etc.*)
 - Can not establish conclusions regarding wind tunnel to flight
- Orbiter assessments use 7.5 degrees for turbulent wedge
 - Could be lower, but insufficient data available
- High Mach/High Enthalpy Turbulent flow is relatively unknown regime
 - Current CFD methods based on ground data, Orbiter heating tools (e.g. XF0002) are based on limited flight data of STS 1-5 (heating uncertainty ≈ 20-30%)
 - Orbiter BLT FE flight data could significantly affect tools, physical models and design/operational predictions

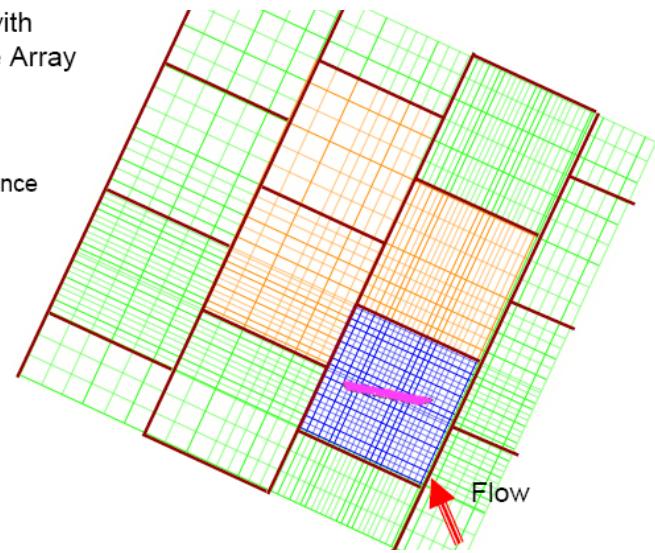


OV-103 Hardware Modifications

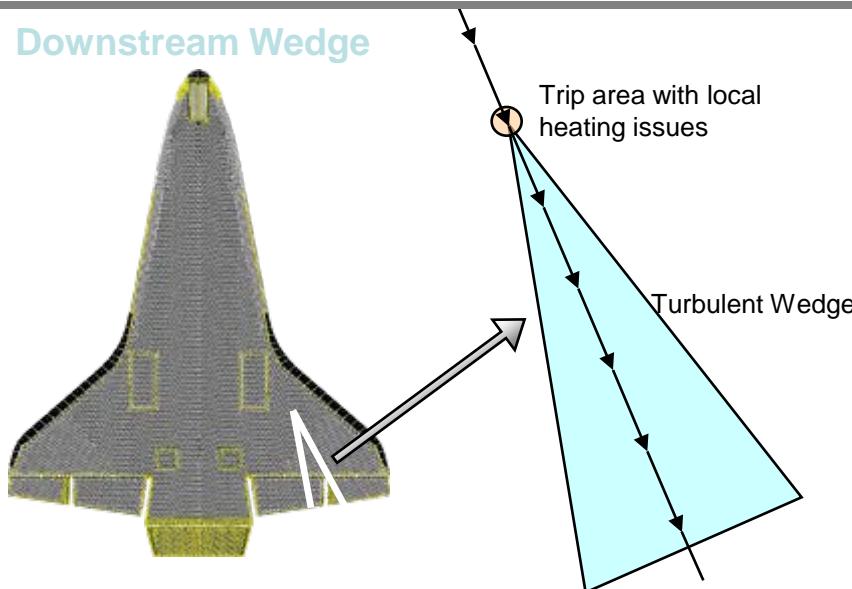
Protuberance Tile



Local Area

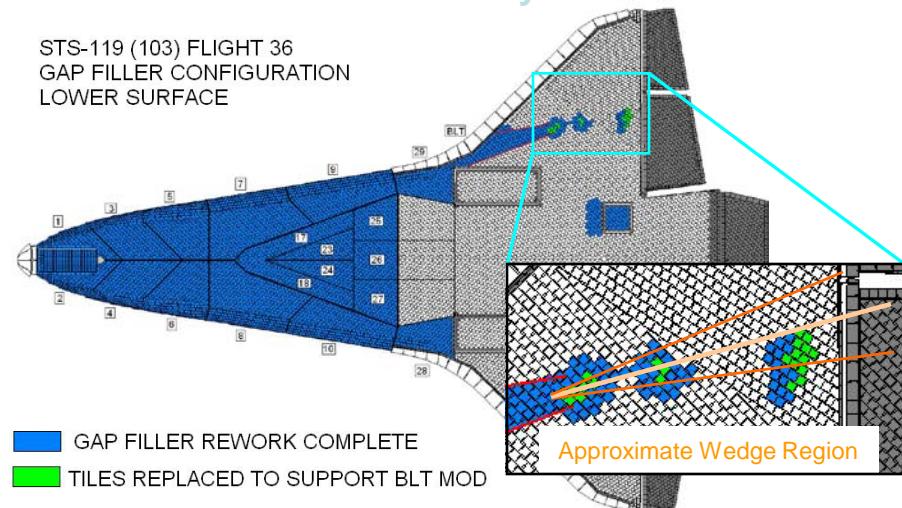


Downstream Wedge



TPS Summary

STS-119 (103) FLIGHT 36
GAP FILLER CONFIGURATION
LOWER SURFACE





HyThirm

Hypersonic Thermodynamic Infrared Measurements



STS-119/STS-125 success criteria: To obtain spatially resolved infrared imagery that will provide a quantified surface temperature map of the Shuttle during hypersonic re-entry

Horvath et. al.
AIAA-2008-4022

04/09 – Mission Success!

Near term goal: Shuttle as target of opportunity to demonstrate thermal imaging capability with existing technologies during Shuttle (STS-119) boundary layer transition flight experiment

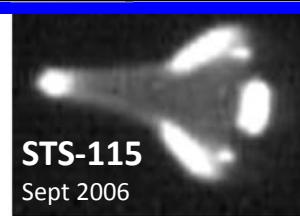
Long term vision: Development of new quantitative state-of-the-art imaging systems (e.g., visual, thermal, spectral) to support a variety of hypersonic flight test programs from an engineering, safety and science perspective

Imagery from “ad hoc” flights
(pre-HYTHIRM)



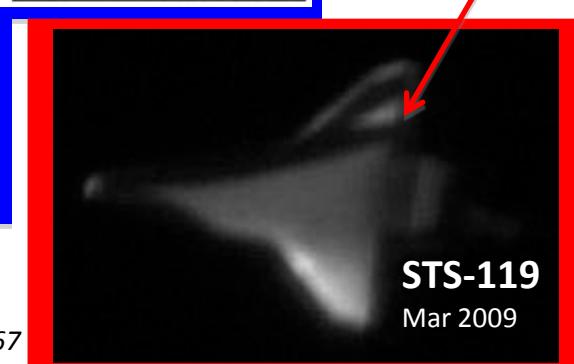
Turbulent flow from gap filler ~ Mach 13

Horvath et. al. AIAA-2007-4267



STS-115
Sept 2006

Turbulent flow from wing protuberance

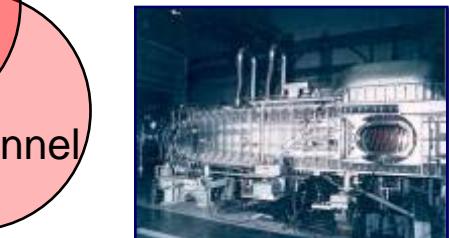
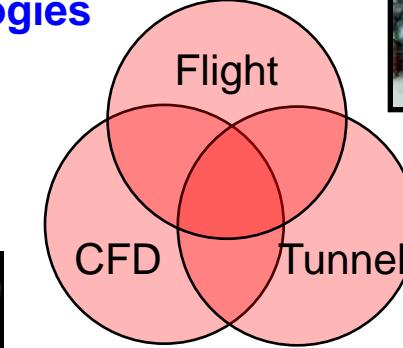
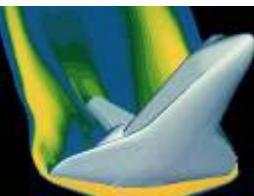
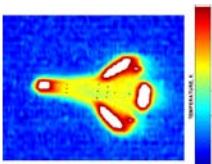


STS-119
Mar 2009



Provide tools required for an integrated test and evaluation approach in which the proper combination of modeling and simulation, ground testing, and flight testing are employed to address of future high speed hypersonic systems

Flight Testing Technologies



Modeling & Simulation

POC's: Thomas.J.Horvath@nasa.gov (PI) and Paul.W.Krasa@nasa.gov (PM)

Sponsors: NASA JSC SSPO; NESC, ARMD

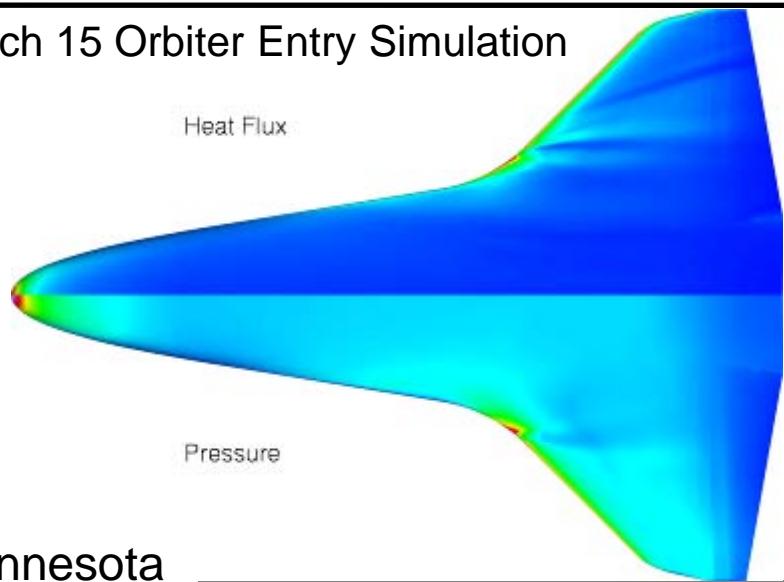
Ground Test Facility Technologies

Orbiter Entry BLT Stability Modeling

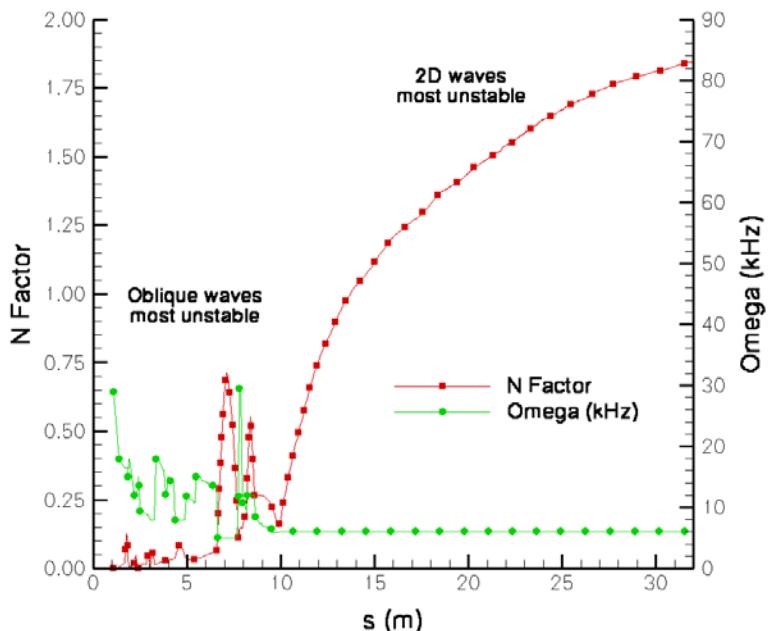
Graham V. Candler
Heath B. Johnson

- 128 million element Orbiter grid provided by NASA
- Solved using U of MN US3D finite-volume solver with 1400 cores
- 5-species air finite-rate thermochemistry
- Centerline flow solution extracted and analyzed using Parabolized Stability Equations in STABL

Mach 15 Orbiter Entry Simulation



University of Minnesota



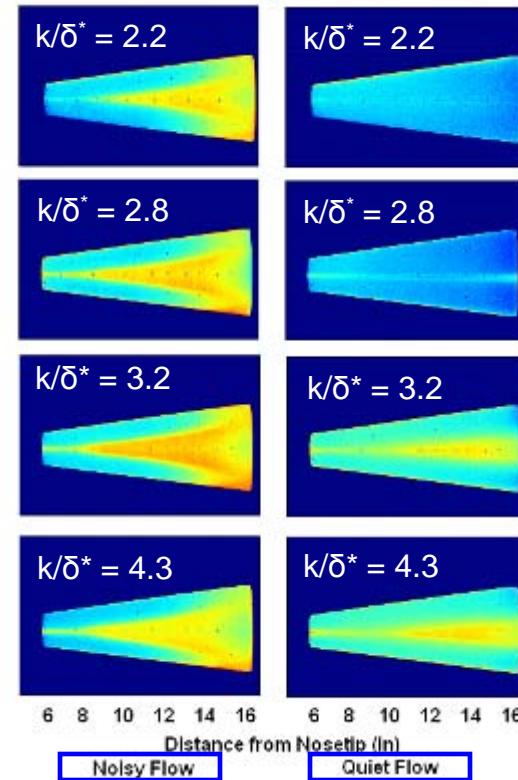
vsn5 May 7, 2009

presenter - Charles H. Campbell / NASA JSC /
charles.h.campbell@nasa.gov

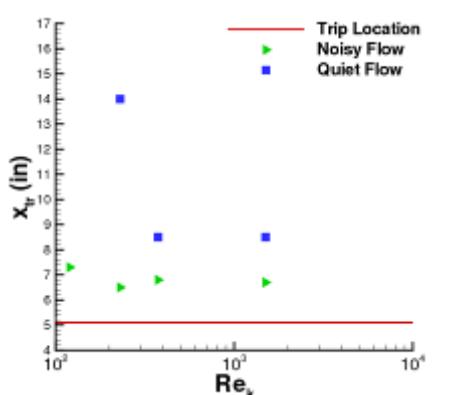
- Demonstrates it is possible to generate stability-quality CFD solutions for Shuttle
- Initial results show N-factor of nearly 2 at rear of shuttle
- Oblique waves dominant near the nose but 2D waves reach higher N
- Currently a centerline flow analysis
- Future results will include off-axis 3D effects in the stability analysis

Purdue Mach 6 Quiet Tunnel

Steven P. Schneider



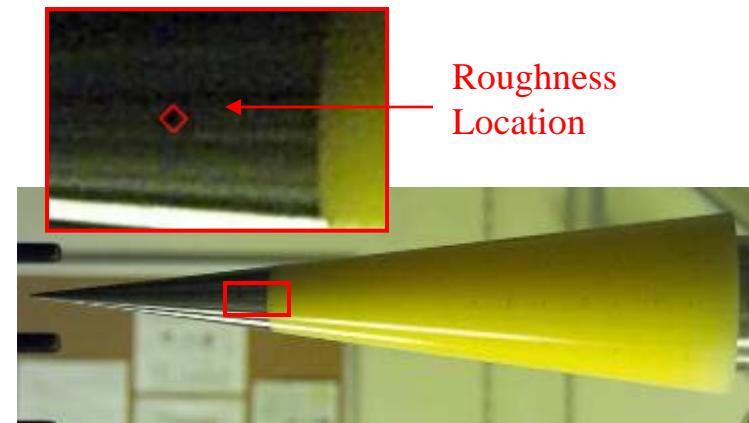
Effect of Tunnel Noise on Roughness-Induced Transition for a Slender Cone at Mach 6



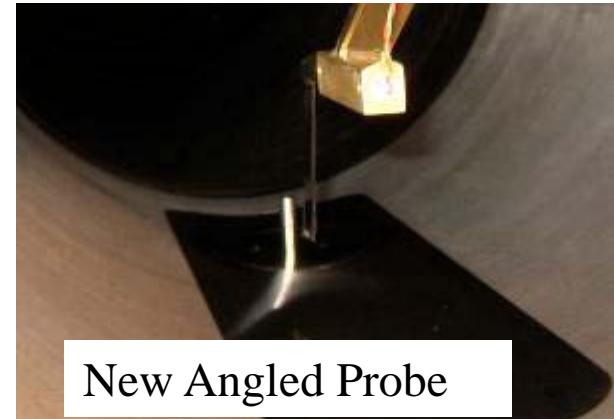
7-deg. half-angle cone,
0.047-in. nose radius, about 3E6/ft.

Ref: Casper et al., AIAA Paper 2008-4291

- Effective trips under noisy flow are not always effective under quiet flow
- When transition did occur under quiet flow, it was always delayed



Hot Wire in Wake of Isolated Roughness



New Angled Probe

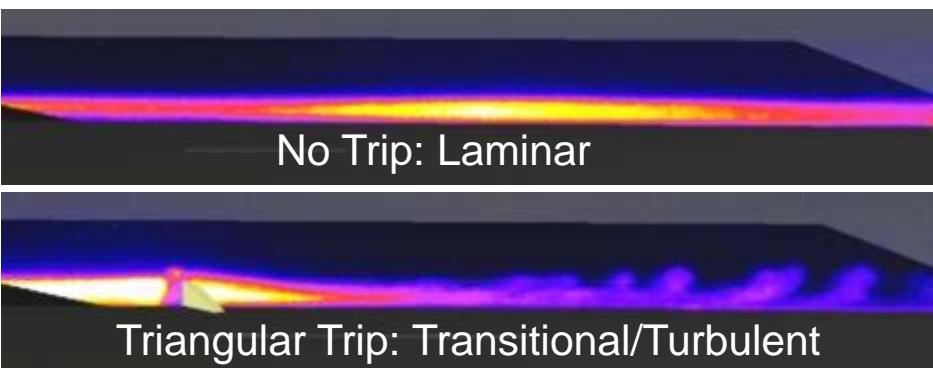
Nitric Oxide PLIF

Danehy, Inman, Bathel, Jones
NASA Langley Research Center

Overview

- Nitric Oxide Planar Laser-Induced Fluorescence (NO PLIF)
 - Pioneered at Stanford in 80's and 90's (Hanson)
- Laser/Camera system visualizes slices of flow
- Quantitative measurements
 - Velocity, temperature
- Used in 31" Mach 10 Wind Tunnel
- Primarily Supported by NASA Fundamental Aero Program, Hypersonics Project

Recent Applications: Transition Studies



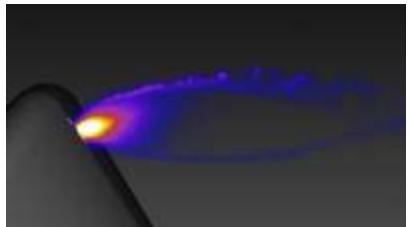
No Trip: Laminar

Triangular Trip: Transitional/Turbulent

Danehy et al., AIAA Paper 2007-0536

- Triangular trip simulates orbiter gap filler
- NO seeds BL fluid, marks flow structures

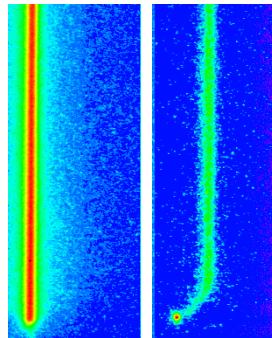
Recent Applications: RCS Jet Imaging



- Measure shape, transition, trajectory, velocity, of RCS jets for both Aero and Aeroheating applications

Inman et al., AIAA Journal (accepted; in press).
Danehy et al., Journal of Spacecraft and Rockets, vol. 46m p. 93-102 (2009).

Future Capabilities



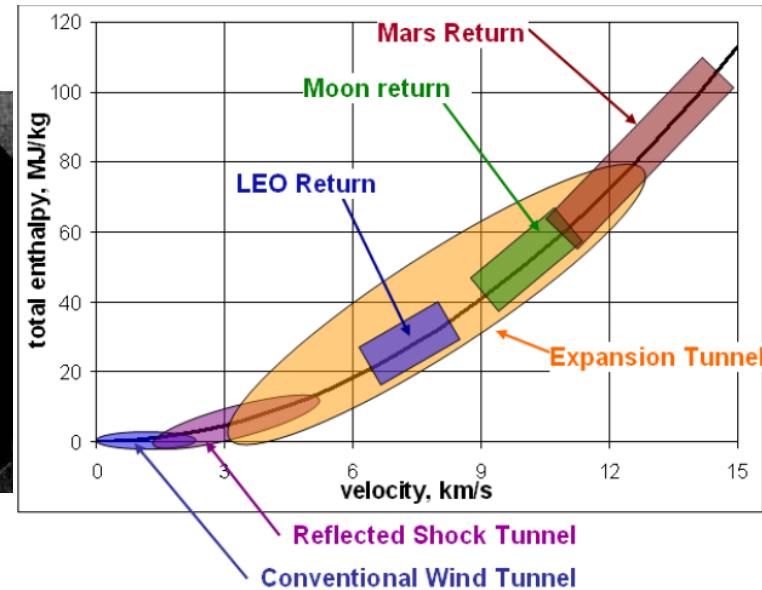
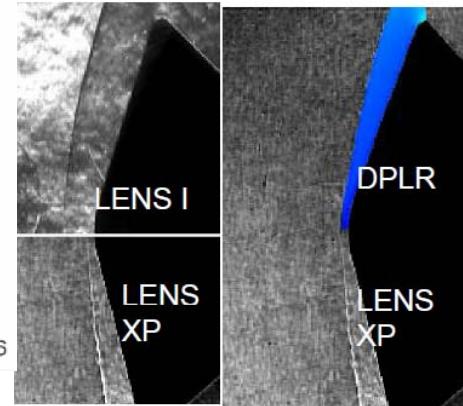
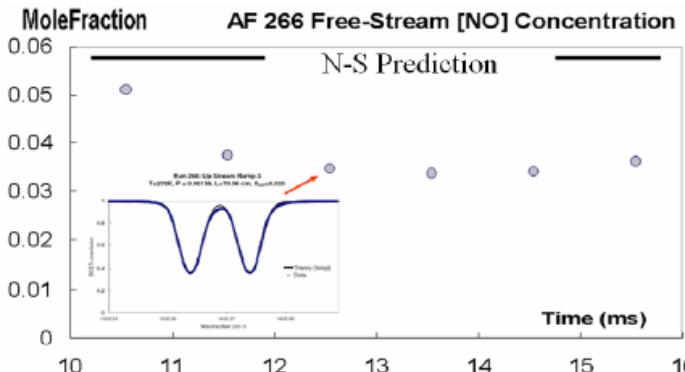
Delay= 0ns

500 ns

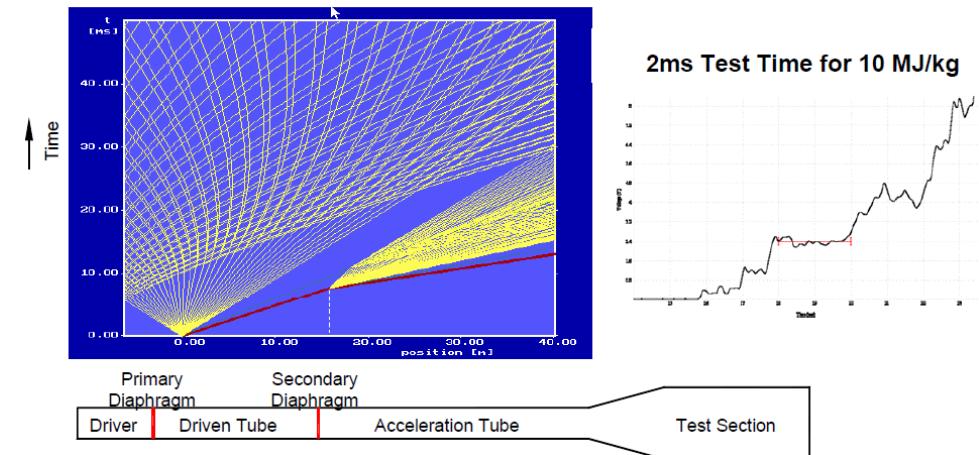
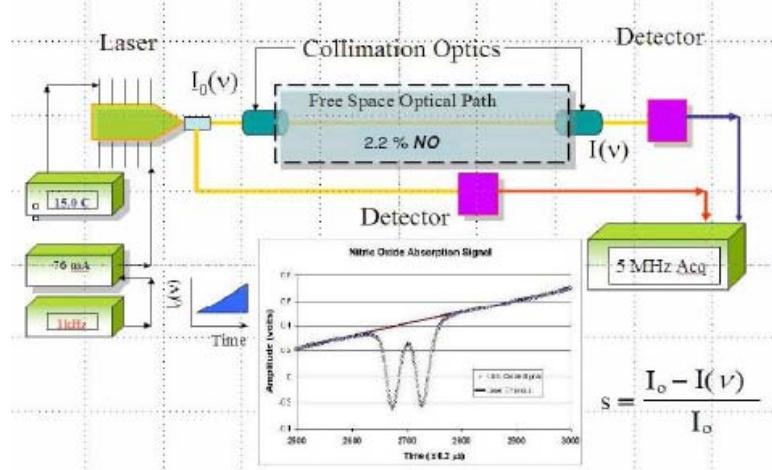
Velocity Measurement
 $velocity = \frac{distance}{time}$

Danehy et al, AIAA Journal v.41, n.2, p. 263-271 (2003).

- High speed imaging, velocimetry:
 - MHz Frame Rate Laser/Camera system (NRA with Ohio State)
- Temperature measurement



Measurements of NO in Freestream and Shock Layers Employing Tunable Diode Laser Spectroscopy



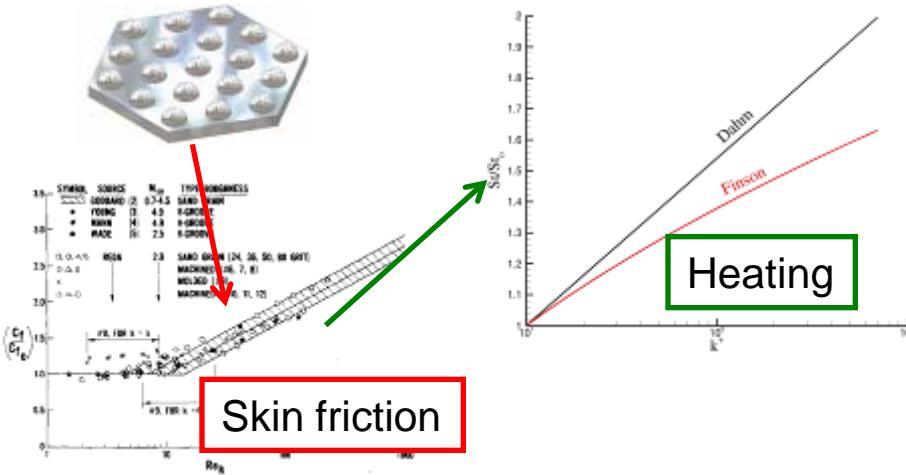
Ref: Wadhams, et al AIAA 2007-551,
Holden et al, AIAA 2008-2505,
MacLean et al, AIAA 2007-121



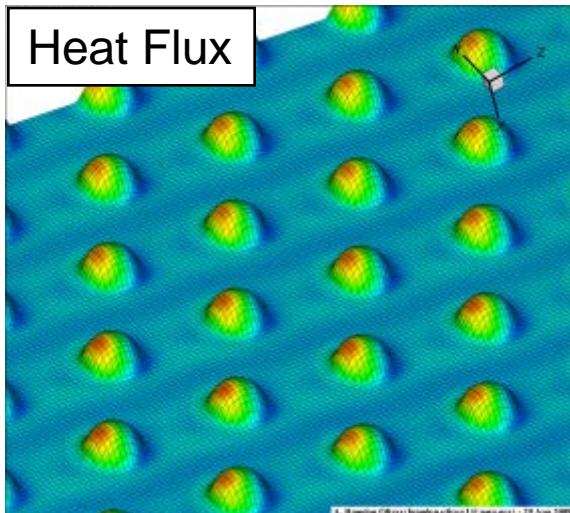
Roughness and Heating Augmentation

Adam Amar and Brandon Oliver / NASA JSC

Geometry/Spacing/Height



Heat Flux



CFD corroborates wind tunnel trend

vsn5 May 7, 2009

presenter - Charles H. Campbell / NASA JSC /
charles.h.campbell@nasa.gov

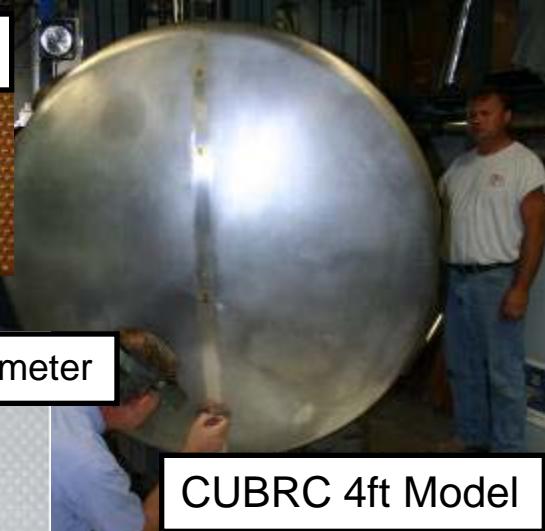
AEDC EDM Model



CUBRC Rough Calorimeter



CUBRC 4ft Model



Orion/CEV testing

- Agrees with historic data
- Shows existing correlations are reasonable

Model will be a function of:

- Roughness geometry
- Smooth wall boundary layer properties

Forward work

- Examine blowing effects on roughness
- Get augmentation data for Avcoat patterns

STS-119 Launch Photo

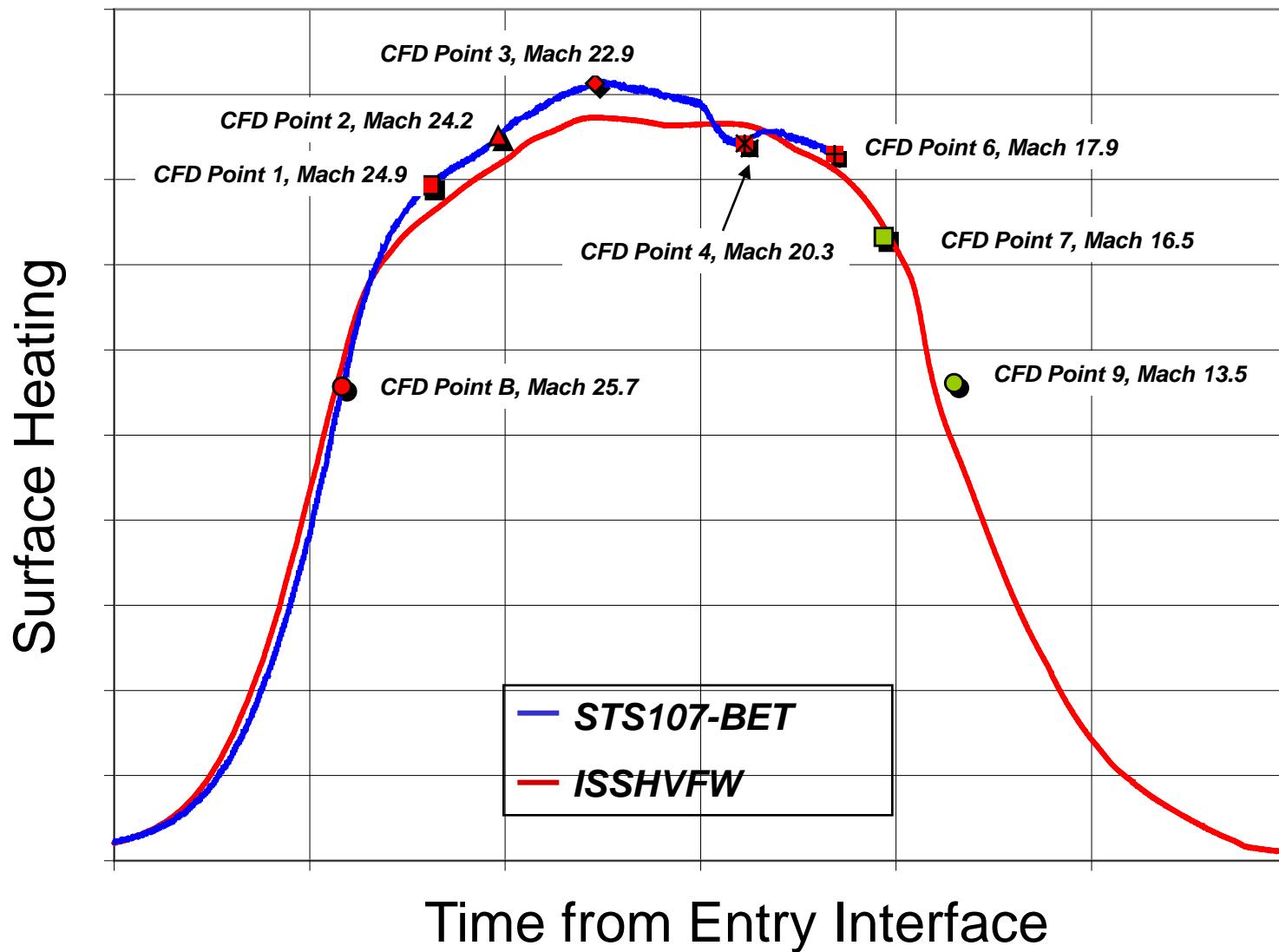


Ryan R. Smith
STS-119, March 15, 2009

Back-up

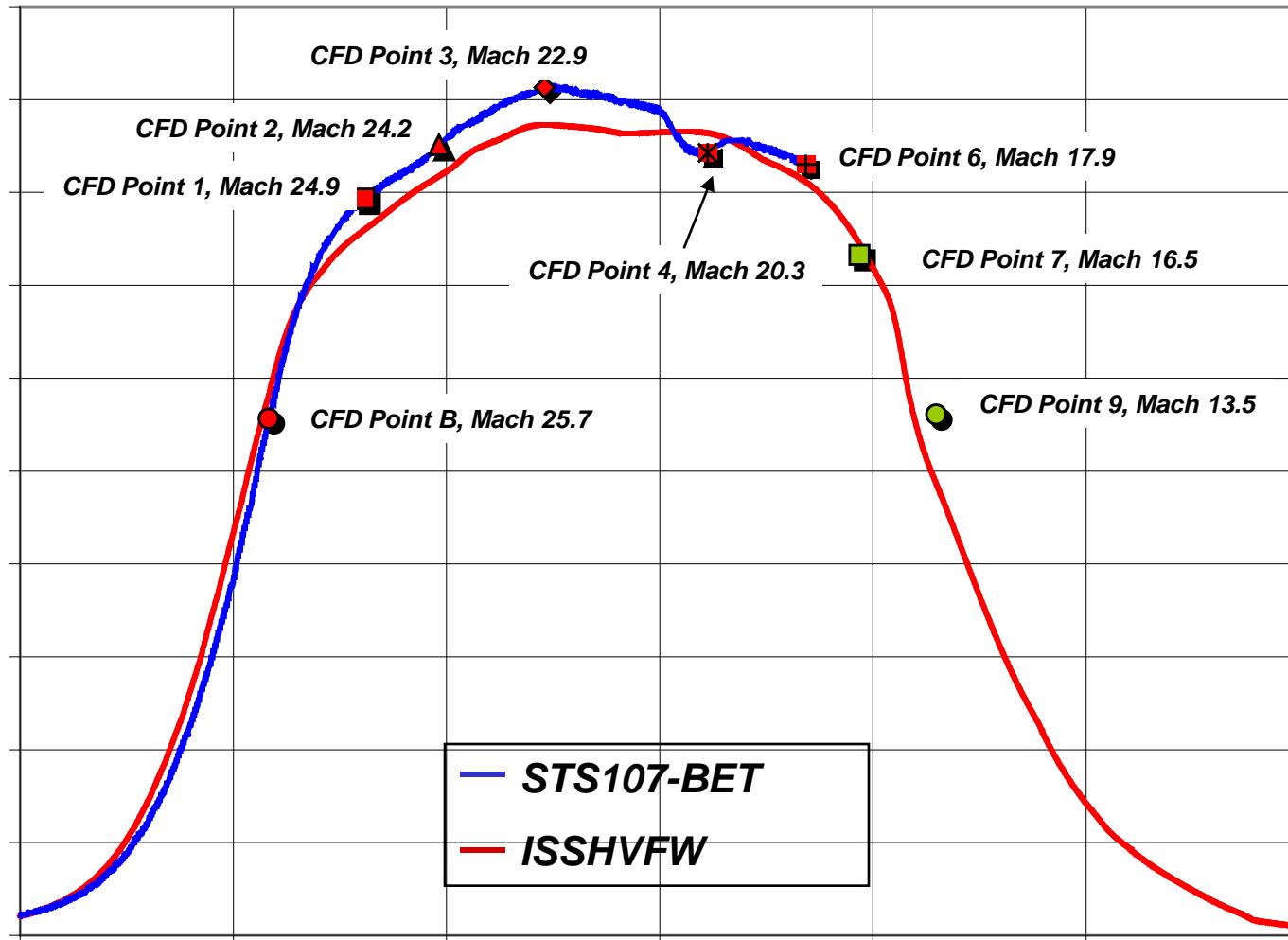


CFD Repository



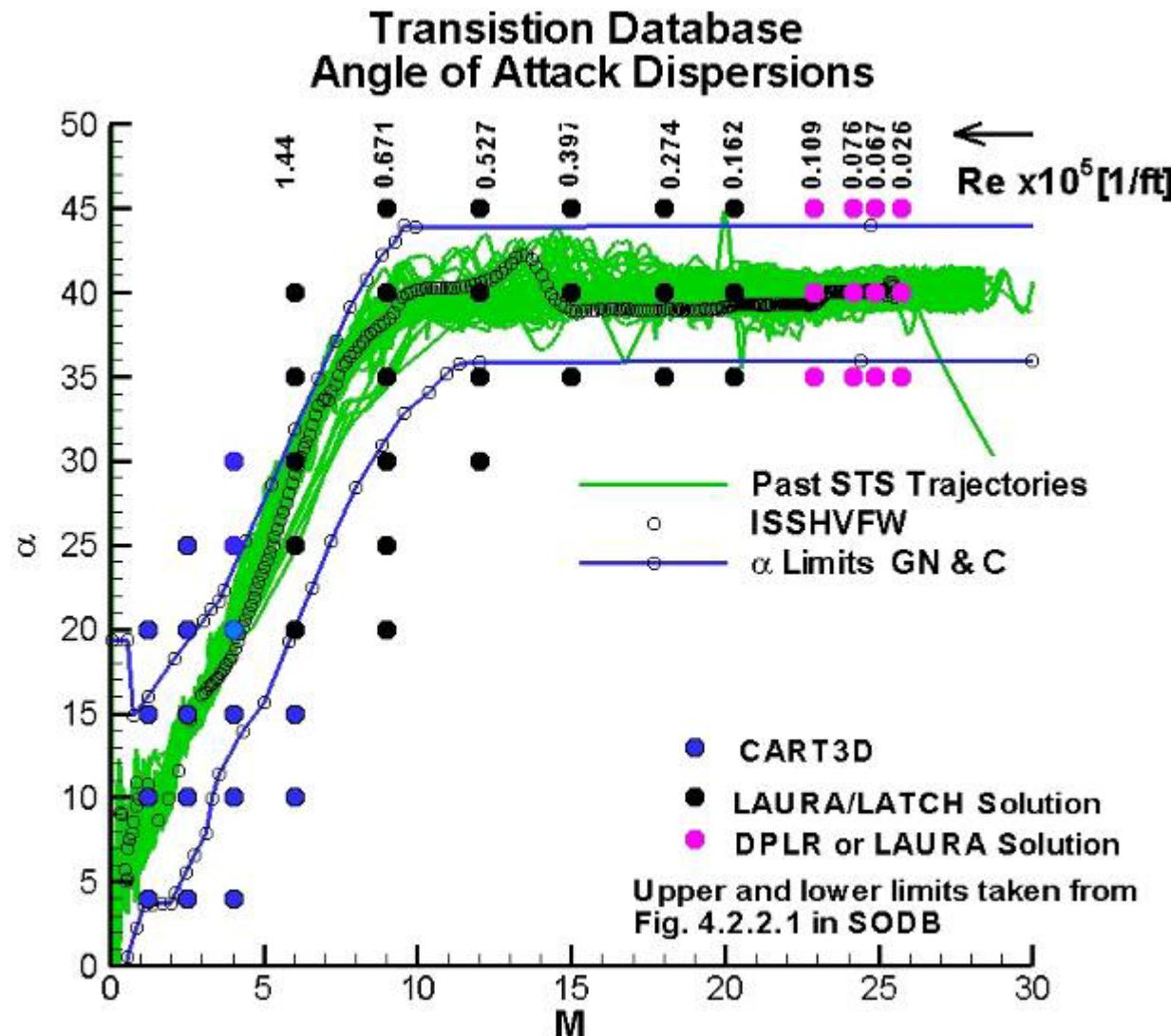
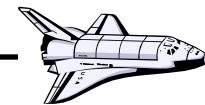


CFD Repository





Boundary Layer Properties DB





Simplified Cavity from Point Cloud

